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IMPLANTABLE ACOUSTIC-BEACON AUTOMATIC FISH-TRACKING SYSTEM

Robert J. Maybue, Ray W. Lovelady,
Robert L. Ferguson, and Clarence E. Richards

Langley Research Center
Hampton, Va. 23665

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16. Abstract

A portable automatic fish-tracking system has been developed by the Langley Research Center for monitoring the two-dimensional movements of small fish within fixed areas of estuarine waters and lakes. By using the miniature pinger previously developed for this application, prototype tests of the system were conducted in the York River near the Virginia Institute of Marine Science with two underwater listening stations. Results from these tests showed that the tracking system could position the miniature pinger signals to within $\pm 2.5^{\circ}$ and ± 135 m at ranges up to 2.5 km. The pingers were implanted in small fish and were successfully tracked at comparable ranges. No changes in either fish behavior or pinger performance were observed as a result of the implantation. Based on results from these prototype tests, it is concluded that the now commercially available system provides an effective approach to underwater tracking of small fish within a fixed area of interest.

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IMPLANTABLE ACOUSTIC-BEACON AUTOMATIC FISH-TRACKING SYSTEM

Robert J. Mayhue, Ray W. Lovelady, Robert L. Ferguson,
and Clarence E. Richards*
Langley Research Center

SUMMARY

The Langley Research Center has developed and tested a portable automatic tracking system for observing the movements of fish, 230 g and larger, in shallow estuarine waters and lakes. A miniature pulsed acoustic beacon (pinger) implanted in a fish gullet was used with two underwater listening stations during evaluation testing in the York River near the facilities of the Virginia Institute of Marine Science (VIMS), who supported the testing. The tests showed that the pinger signals from the instrumented fish could be located to within $\pm 2.5^{\circ}$ and ± 135 m at ranges up to 2.5 km. The instrumented fish showed no changes in behavior during the tests, and the performance of the pingers was unaffected by implantation. The now commercially available automatic fish-tracking system could substantially increase knowledge and information about free-swimming fish movements and, at the same time, greatly reduce manpower requirements and other operational problems associated with fish tagging and tracking.

INTRODUCTION

Marine biologists and industrial fisheries, as well as others, need more detailed information about free-swimming fish behavior than presently exists, both to increase scientific understanding and to improve methods of fish-crop management, including such things as increasing fish-crop yield. Conventional methods of monitoring fish movement (for example, tagging and tracking by boat) are encumbered by extensive manpower requirements and navigational and operational problems. In order to alleviate these problems, the Langley Research Center, with the aid and support of the Virginia Institute of Marine Science (VIMS), has developed and tested a portable pulsed acoustic-beacon (hereinafter referred to as the pinger) fish-tracking system to monitor fish movements. This system not only greatly alleviates the operational fish-tracking problems at far less manpower requirements but can also increase angular and range position accuracy of fish-position determination.

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*Virginia Institute of Marine Science, Gloucester Point, Virginia.

Evaluation tests of a two-station prototype tracking system were conducted in the York River in the vicinity of VIMS during the summer and fall of 1975. As described in reference 1, the pinger that was employed for this investigation and which is now commercially available was originally developed by Langley Research Center for tracking fish 230 g or larger. (Another application of the pinger is presented in ref. 2.) The underwater listening stations and data-acquisition subsystems were designed and fabricated under contract, with contractor personnel actively participating in the testing and reporting (ref. 3). This report describes both the prototype-system components and the results from field tests, and also includes an appendix by Richard N. Green which presents an analytical study of tracking accuracy.

SYSTEM DESCRIPTION

Principles of Operation

Figure 1 illustrates the prototype test installation of the fish-tracking system. Detection of signals from the pinger implanted in a fish is accomplished by hydrophone listening stations with above-surface radio telemeters which relay data to a shore data base for display and recording. All system controls emanate from the shore data base which can be operated in either a manual or an automatic mode. If sufficient acoustic frequency separation is maintained to avoid interference, several pingers can be tracked within a given tracking region. All components of the system are portable, and up to 16 listening stations can be controlled from the data base.

The underwater listening station has twelve, 30° beam width hydrophone receiver sections arranged in a circular array about an open center so that the array can be mounted at a fixed depth on a support pole. The 12 hydrophones simultaneously monitor their environment to provide continuous, 360° reception of acoustic signals within range. Angular location of the instrumented fish is determined from identification of the two hydrophone sections which are receiving the strongest signals. Technical specifications for the system are listed in table I.

Fish Pinger

Figure 2 is a photograph of an expendable pinger, similar to those used for the tracking-system tests. The pinger is battery powered and radiates, about once per second, a nominal, 30.0 Pa, omnidirectional acoustic pulse with a duration of 7 to 10 msec at a precise frequency within the 30- to 40-kHz band. (The repetition rate, which is specified at the time of manufacture, can be varied between 1/2 and 2 pulses/sec, and can be utilized to measure pinger environment temperature although this feature was not used

in this test program.) The operating lifetime of tne pinger is a function of the self-contained battery cell drain and, in this program, was typically 7 to 10 days. Specifications for the commercially available pinger are given in table II.

Listening Station

Figure 3 presents pnotographs of the components of the underwater prototype listening station. The circular array of 12 hydrophones, the cable to the above-surface radio telemeter, and the calibration pinger mounted on the top cover of the hydrophone case are shown in figure 3(a). Figure 3(b) shows the electronic modules of the 12 hydrophone sections.

Block diagrams of the listening station of the fish-tracking system are presented in figure 4. Figure 4(a) shows one of the hydrophone channels and its receiver electronics. The output signal of each channel is compared with that of all other channels to identify the channel with the strongest and second strongest signal. The channel with the strongest signal indicates the coarse angle (within 15^{o}) to the instrumented fish with respect to hydrophone 12, which is used as the angular reference. The receiver amplifiers are automatically gain controlled over a 94-dB range by a voltage which is derived from the highest signal level of any of the 12 receiver amplifiers. The summed output of the hydrophone receiver channels is then applied to logic electronics (fig. 4(b)). The ratio of the strongest signal to the second strongest signal, which represents the angular displacement of the instrumented fish with respect to the angular orientation of the hydrophone with the strongest signal. is also determined in the logic electronics. This ratio is then used to find a fine angle correction to the coarse angle determination that was previously made. The fine angle corrections are in $\pm 2.5^{o}$ intervals and about the $\pm 2.5^{o}$, $\pm 7.5^{o}$, and $\pm 12.5^{o}$ sectors of the $\pm 15^{o}$ coarse angle interval. The incoming 18-bit and outgoing 46-bit data stream is encoded and decoded in the logic electronics. Table III lists the digital bit stream identification. The listening-station logic electronics also decodes mode control commands from the shore data base so that each listening station may be switched into one of the four functional modes shown in the following table:

Mode	Function
Active	Tracking fish pinger
Standby	Minimum power consumption
Calibrate	Tone transmission for determining angular positions of other stations
Audiotone	Signal from listening station

Data Base

A block diagram of the shore data base circuitry is presented in figure 4(c). Digital control command signals for listening station selection, operational mode selection, and frequency tuning are entered into the data base memory from front panel controls and are telemetered to the listening station by programed interrogation command.

Data from each listening station can be acquired by programed interrogation commands or acquired sequentially in the automatic mode. For the tracking exercises of this investigation where only two listening stations were deployed, alternating interrogations were used.

The angular position of the instrumented fish derived from the incoming tracking data is added to the initial calibration angle stored in the data-base memory to give the angular location of the fish with respect to each listening station. The listening-station data are simultaneously translated into a numerical-display format by the data-base circuitry and into a binary-coded format for recording on paper tape. The temperature of the fish pinger equipped to make the measurement can also be displayed and recorded at the data base.

The data base also provides an audiotone output proportional to the summed signal outputs of the 12 receivers in the listening stations when the stations are operated in the previously mentioned audio modes. In an audio mode, the frequency of the pinger transmitter is heterodyned to 3 kHz by a frequency-synthesizer local oscillator in the listening station and is relayed to a tuning meter and speaker in the data base. The hydrophone receiver channel listening frequency can be selected in 100-Hz steps, and the tuning meter on the data-base panel displays the difference between the listening frequency and the fish pinger transmitter frequency. An out-of-bound indicator bit which is derived from received pinger signal strength is included in the tracking data stream to indicate when the pinger is beyond reliable tracking range. The data-base components are packaged in a portable case (fig. 5) with the display and control panel on the outside and electronic circuitry on the inside. Connector terminals are provided to the battery-pack power supply, to the punched paper-tape recorder, and to a remote terminal for preprogramed automatic operation.

Radio Telemeter

Figure 6 is a photograph of the two-way radio telemeter that was mounted on the listening-station support pole above the water. The 12-V battery shown in the figure provided power for the listening station. A night light is mounted against the side of the enclosure. Interfacing circuitry between the telemeter transceiver and listening station performs both transmit and receive switching and power-supply regulation.

Data Recording

The data base provides a punched paper-tape record. This paper-tape record can be converted to x-y plots of fish position by a processor developed for this purpose. The paper-tape record can also be translated into alphanumeric format for manual plotting of fish tracks.

EXPERIMENTAL METHODS

Pinger Implantation Effects

Tank studies were conducted at VIMS to determine the effects of pinger implantation on fish behavior and the effects, if any, of implantation on pinger performance. The pinger was inserted into the gullet of a fish specimen as shown in figure 7 and its behavior monitored in a holding tank for 10 days. No changes in either the behavior of the instrumented fish or in its community behavior with other fish were observed. An autopsy on the instrumented fish showed that no significant physical damage resulted from implantation of the pinger during the test period.

Field Installation

Underwater listening stations.- Two prototype listening stations were installed along the 5.5-m bottom contour in the York River near the facilities of VIMS. These stations were mounted on poles at a depth of approximately 3.1 m at high tide. Figure 8 is a photograph of one of the station installations. The locations of the two stations (designated A and B), as shown in figure 9, were determined by transit survey using U.S. National Ocean Survey (formerly U.S. Coast and Geodetic Survey) reference monuments at Quarter 2 (Quarter Point Station) and Iager (Iager Station). The base line between the two stations was 1.22 km long at 103° from magnetic North.

Transit-tracking range.- Three transits were used to obtain comparative position measurements for the evaluation of system tracking performance. One transit site was established on the roof of the VIMS administration building where the data base was situated. The location of this transit was fixed by sightings from the other two transit sites at Quarter Point and Iager Stations (φ_{QI} and φ_{IQ}, respectively, in fig. 9). The transits were used either to position a boat with a submerged pinger or to locate a surface float with a submerged pinger (free or implanted in a fish). The transits measured the angles φ_V, φ_Q, and φ_I during the tests. (See fig. 9.)

Listening-station calibration.- Since each station determines the angle to a pinger with respect to its hydrophone 12, a knowledge of the angular orientation of hydrophone 12 with respect to a fixed reference is required to locate the pinger within the tracking range. As previously stated, a calibration pinger (fig. 3(a)) of known frequency was

installed on each of the two listening stations for this purpose. To find the position of hydrophone 12 of one station, the calibration pinger of the other was activated. The station being calibrated received this signal and computed the angle of its hydrophone 12 with respect to the base line between the two stations. This procedure was reversed to find the angle between hydrophone 12 of the other station and the base line. These angles were measured clockwise from hydrophone 12 of each station and are labeled α_A and α_B in figure 10. Since the angle between the base line and North is known from the transit survey, a calibration angle can be computed for each station (γ_A and γ_B in fig. 10). These two calibration angles are entered into the data base computer memory and the readout angle to the pinger was given clockwise from North.

FIELD TEST RESULTS

Pinger Tests

Figures 11(a) to 11(c) present typical plots of the positions of a boat with a submerged pinger as measured by the transits and the positions of the pinger simultaneously measured by the tracking system. The intersections of the three transit sightings were used to evaluate the accuracy of the fish-tracking system. Although a few of the comparative measurements in figure 11 show large differences at long ranges, most of the data from the two sets of measurements agreed to within ±135 m. The tracking comparison of figure 11(c) gives an indication of the range capability of the system, where data point 10 was 2.5 km from the upstream listening station.

An indication of system-tracking accuracy is graphically illustrated in figure 11(d). In this plot, error bands caused by the $\pm 2.5^{\circ}$ position measurement deviation of the fish-tracking system are superimposed on the transit data points of figure 11(c). A 3° constant was added to the fish-tracking system data because analysis of the data trends of figure 11(c) showed a bias attributable to error in the angular position calibration of the listening stations. Figure 11(d) shows that all pinger position error bands either contained or were very close to the transit point. An analysis of the accuracy of the fish-tracking system is included in the appendix.

Fish-Tracking Tests

The first series of fish-tracking tests were conducted in the summer of 1975 with a bluefish (454 g) and a spot (230 g) to verify system performance with implanted pingers. The listening stations acquired pinger signals in excess of 1.85 km. However, no useful angular position data were obtained because upstream station B developed a hydrophone leak.

Fish-tracking tests were resumed in late November 1975 with a hybrid striped-bass-perch tank specimen supplied by VIMS. For these tracking exercises, the 700-g hybrid fish was tethered to a small surface float in early tests for ease of recovery and later released for free-swimming tracking.

Results obtained from tracking the tethered and free-swimming hybrid fish are presented in figure 12. The system was also successfully used to direct the recovery boat to the fish during tethered tests. Although fish behavior study was not an objective of these exercises, figure 12 shows that the free-swimming instrumented fish swam toward shore.

The results of these fish-tracking tests and the pinger tests described in the previous section show that the prototype fish-tracking system provides an effective method for automatic monitoring of the movements of fish within a prescribed area. The commercially available system components are easily transportable to other areas of interest.

Although not tested during the tracking exercises described in this report, the fish-tracking system is also capable of measuring the pinger environment temperature. With further development, the system could also provide a water-depth measurement at the pinger. With these additional measurements, the system offers greatly expanded data on fish movements and behavior to fishery scientists.

CONCLUDING REMARKS

A miniature acoustic beacon (pinger) developed for implantation into fish 230 g or larger in size was tested in the York River with two prototype underwater omnidirectional listening stations near the facilities of the Virginia Institute for Marine Science during the summer and fall of 1975. Comparative measurements with shore-based transit sightings showed that the fish-tracking system could locate pinger signals to within $\pm 2.5^{o}$ and ± 135 m at ranges to 2.5 km. Implantation of the pinger caused no observable changes in fish behavior or in pinger performance.

The fish-tracking system described in this report is effective for monitoring fish movements within a fixed area of interest. In addition to providing a reduction of man-power and solving other operational problems associated with fish tagging and manual tracking, the commercially available system also offers improvement in fish-tracking accuracy and is readily transportable to other sites. Although the system of this report

was developed for use in shallow waters, it could be easily modified for deep-water applications within specified tracking ranges.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
August 1, 1977

APPENDIX

EFFECT OF SYSTEM ERROR ON FISH-TRACKING ACCURACY

Richard N. Green
Langley Research Center

SYMBOLS

$g(\theta_1,\theta_2)$	arbitrary function
l	length of base line
P	probability
R	circular probability area
X	axis
x	actual position coordinate parallel to base line
$\hat{x}$	estimated position coordinate parallel to base line
Y	axis
y	actual position coordinate perpendicular to base line
$\hat{y}$	estimated position coordinate perpendicular to base line
δ	angular position error
θ	actual angular position from true North
$\hat{\theta}$	estimated angular position from true North
ρ	distance from midpoint of equal probability area to position coordinates

APPENDIX

Subscripts:

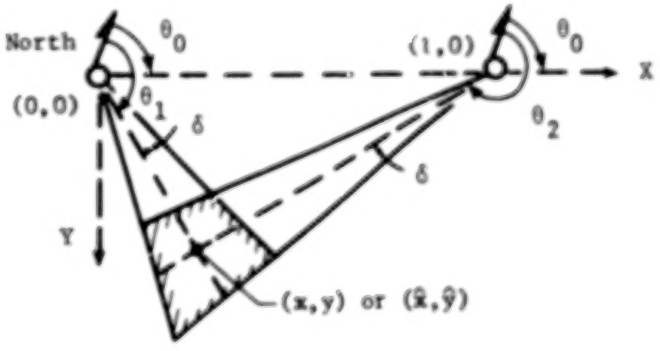
0	base line reference
1,2	listening-station identification

ANALYSIS

If there are errors in the measurements of the angular position of the fish, the geographic coordinates of the fish will also contain errors. Referring to the following sketch, the measurements θ_1 and θ_2 provide an estimate of $\hat{x}$ and $\hat{y}$ coordinates of the fish from the equations:

$$\hat{x} = \left[\frac{\sin(\theta_2 - \theta_0)\cos(\theta_1 - \theta_0)}{\sin(\theta_2 - \theta_1)}\right] l \tag{A1}$$

$$\hat{y} = \left[\frac{\sin(\theta_2 - \theta_0)\sin(\theta_1 - \theta_0)}{\sin(\theta_2 - \theta_1)}\right] l \tag{A2}$$



The actual position of the fish (x,y), corresponding to the actual measurement (θ_1,θ_2), must be within the shaded area since $(\hat{\theta}_i - \delta) < \theta_i < (\hat{\theta}_i + \delta)$ where $i = 1$ or 2. The probability that the actual position (x,y) is within the diamond centered at $(\hat{x},\hat{y})$ is one since θ_1 and θ_2 are distributed uniformly. The probability density function of the actual angle measurements is as follows:

$$g(\theta_1,\theta_2) = \frac{\sin(\hat{\theta}_2 - \hat{\theta}_1)}{4\delta^2 l^2 \sin(\hat{\theta}_2 - \theta_0)\sin(\hat{\theta}_1 - \theta_0)} \tag{A3}$$

APPENDIX

This is a good indication of how accurately the fish can be located since, for a small circle denoted R and centered at $(\hat{\theta}_1, \hat{\theta}_2)$, the probability that the fish is within it is given by the following equation:

$$P\left[(\theta_1, \theta_2) \in R\right] = \int_R g(\theta_1, \theta_2)\, dR \tag{A4}$$

If the parameter of accuracy is the radius of a circle which contains a certain probability of containing the true point, the integration of equation (A4) to solve for R gives the desired probability level. This calculation is very difficult. An equivalent approach to determine the radius r was taken. The angular intervals $(\theta_1 \pm \delta)$ and $(\theta_2 \pm \delta)$ were divided into 10 equal angular increments; this corresponds to dividing the diamond area in the previous sketch into 100 equal probability areas. The distance ρ from the midpoint of each small area to the midpoint of the diamond was then calculated. The 100 distances were then ordered according to magnitude such that the largest of the ρ became the 100th ρ. Thus, the distance error is less than or equal to ρ_{100}. Likewise a 95-percent confidence circle is one with a radius of ρ_{95}. Numerical results from this approach are presented in figure A1. These results are in the form of a contour map with an accuracy that can be expected from a tracking system with two listening stations in the York River having a system angular error of $\delta = \pm 2.5^{\circ}$. In figure A1, the most accurate measurement that can be expected with 95 percent confidence is made at about 42.4 m along the perpendicular bisector of the base line. At the outer edges of the tracking range, the fish position will be measured to within about 303 m with 95 percent confidence.

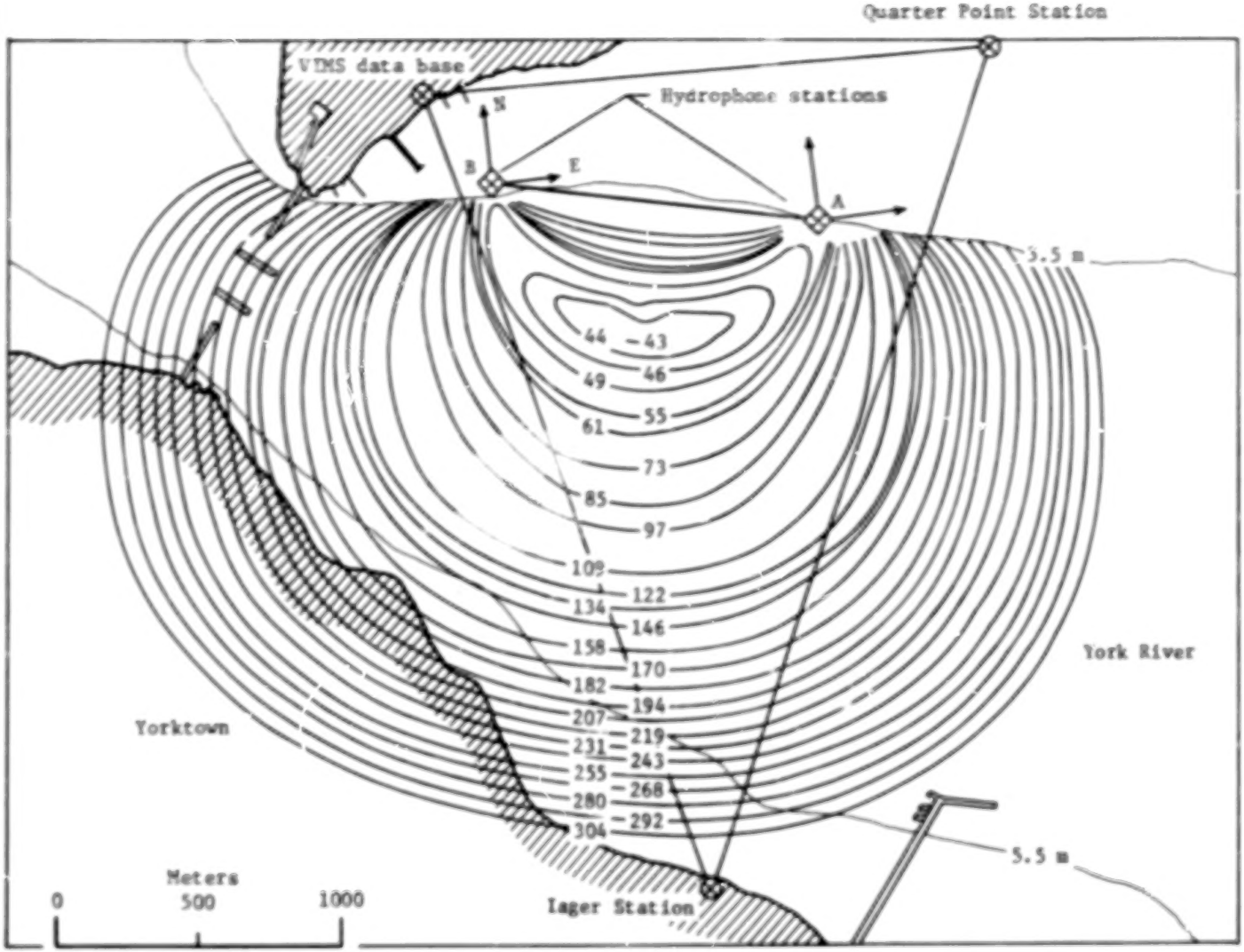


Figure A1.- Accuracy contours in meters (95 percent confidence with $\pm 2.5^{o}$ error).

REFERENCES

1. Lovelady, Ray W.; and Ferguson, Robert L.: Minature Sonar Fish Tag. NASA Tech Brief B75-10092, June 1975.

2. Mayhue, Robert J.; and Lovelady, Ray W.: Acoustic Tracking of Woodhead Seabed Drifters. NASA TN D-8392, 1977.

3. Osborne, P. W.; Hoffman, E.; Merriner, J. W.; Richards, C. E.; and Lovelady, R. W.: Automatic Electronic Fish Tracking System. OCEANS '76, IEEE Publ. No. 76 CH 1118-9 OEC, c.1976 pp. 15A-1 – 15A-6.

TABLE I.- LISTENING-STATION SPECIFICATIONS

Receiver sensitivity, dB (re: 1 Pa at 1 m)	-39
Resolution, deg	±2.5
System frequency band, kHz	30 to 40
Receiver bandwidth, Hz	100
Hydrophone responsivity, dB (re: 1 V/Pa)	-75
Hydrophone beam width in horizontal plane, deg	30
Calibration pinger frequency at –	
Station A, kHz	36.6
Station B, kHz	36.9
rf link frequency, MHz	171.150
Temperature indication for 0.5-2.0 pulses/sec, °C	4.4 to 36.7
Power:	
Supplied by 12-V dc battery, A-hr	30
Demand from 12-V dc battery –	
Standby, mA	50
Average active, mA	300
Calibrate, mA	300
Audiotone, mA	600
Dimensions for –	
Listening station (o.d. × i.d. × height), cm	40.6 × 14.0 × 19.1
rf station (height × width × depth), cm	63.5 × 35.6 × 15.2
Weight:	
Listening station in –	
Air, kg	18.1
Water, kg	4.5
rf station, kg	13.6

TABLE II.- FISH PINGER SPECIFICATIONS

Operating frequency (selectable), kHz	30 to 40
Operating depth, m	305
Pulse duration, msec	7 to 10
Pulse repetition rate (function of temperature), pulses/sec	0.5 to 2.0
Acoustic output (minimum average at 1 m normal to long axis), Pa	30.0
Operating temperature, ^{o}C	-2 to 38
Storage temperature (without battery), ^{o}C	-54 to 74
Operating life (battery dependent), days	7 to 10
Dimensions (length × diameter), cm	3.8 × 1.5
Weight (including battery) in –	
Air, g	15
Water, g	8
Power for 4-V battery, mA	250

TABLE III.- DIGITAL BIT STREAM

(a) Data transmitted from listening station to data base

Item	Bits
Strongest receiver identification	12
Second strongest receiver identification	12
Fine angle	2
Automatic gain control	6
Listening-station identification	7
Signal out of bounds	1
Temperature	6
Total	46

(b) Data transmitted from data base to listening station

Item	Bits
Listening-station identification	7
Frequency select	6
Transmit time slot	2
Mode select	3
Total	18

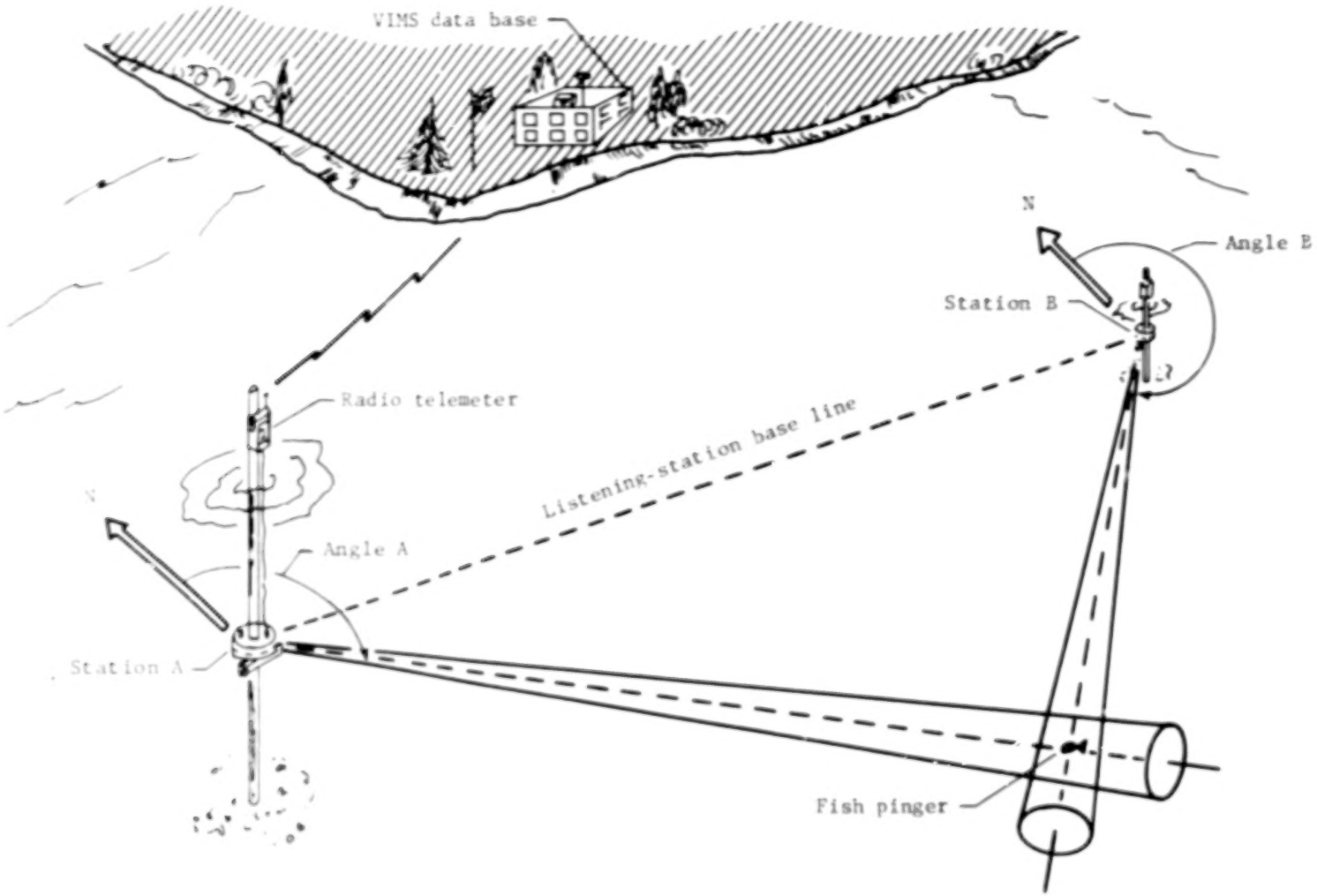


Figure 1.- Prototype test installation in York River.

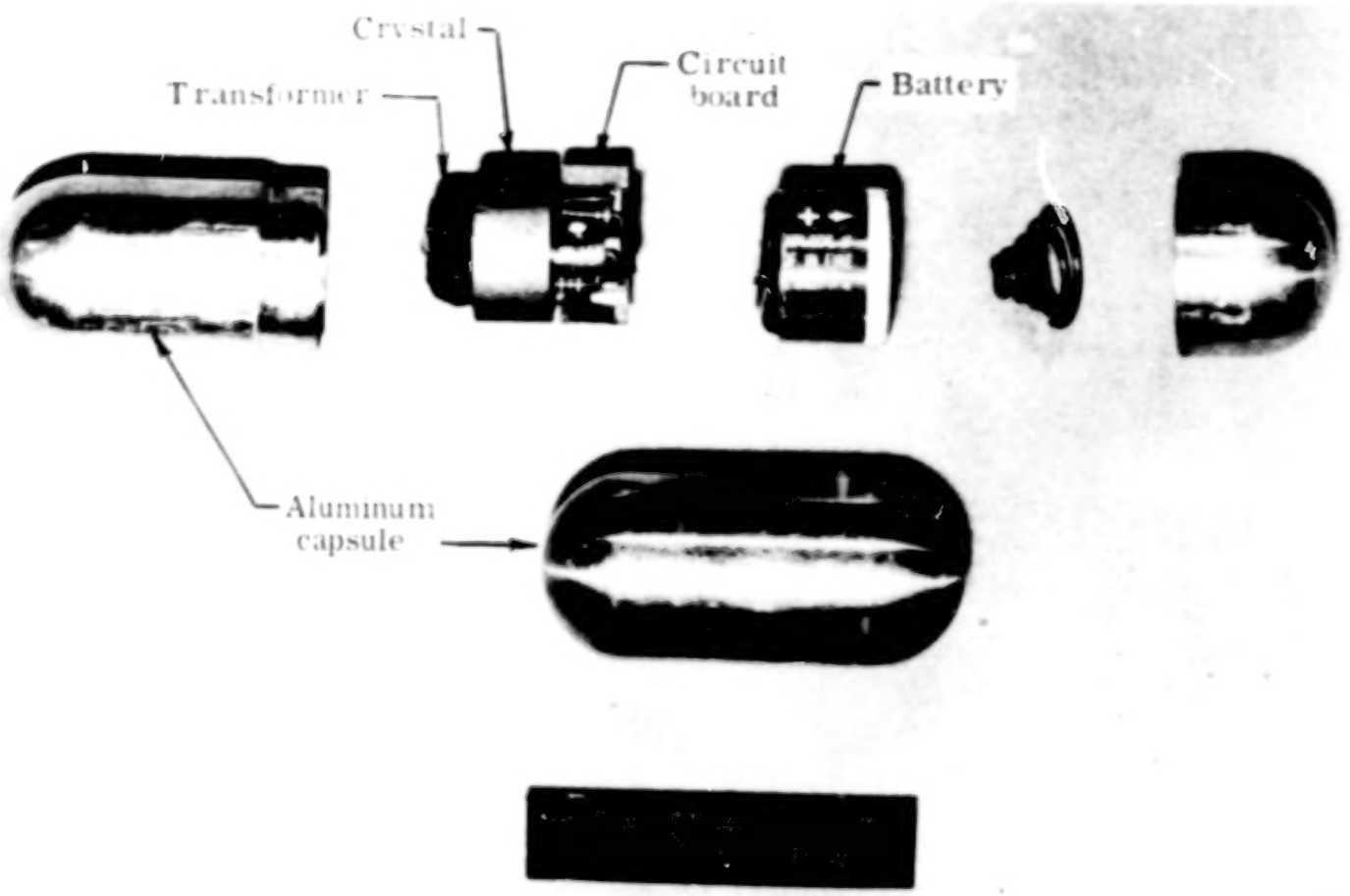


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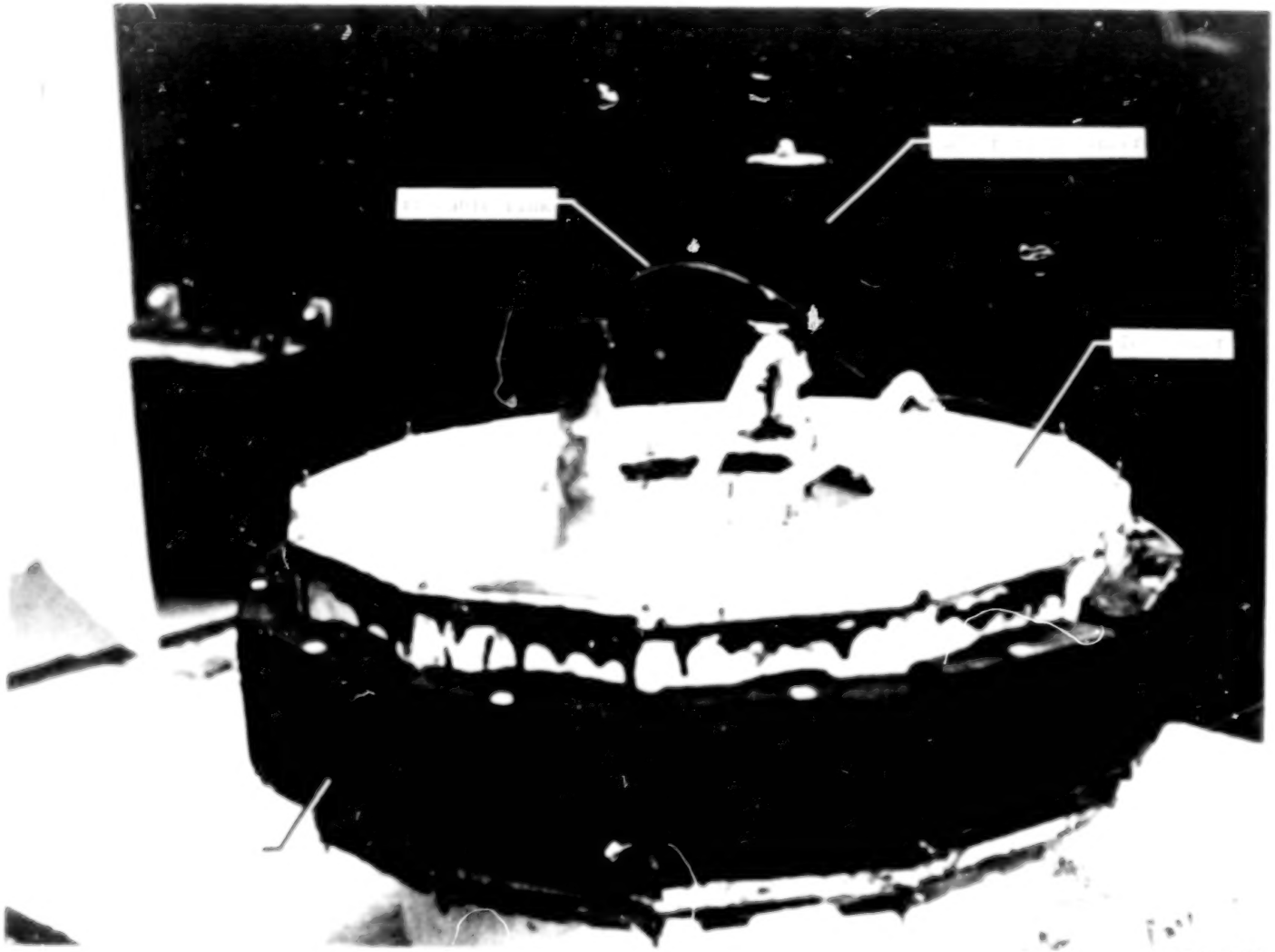
Figure 2.- Fish pinger.



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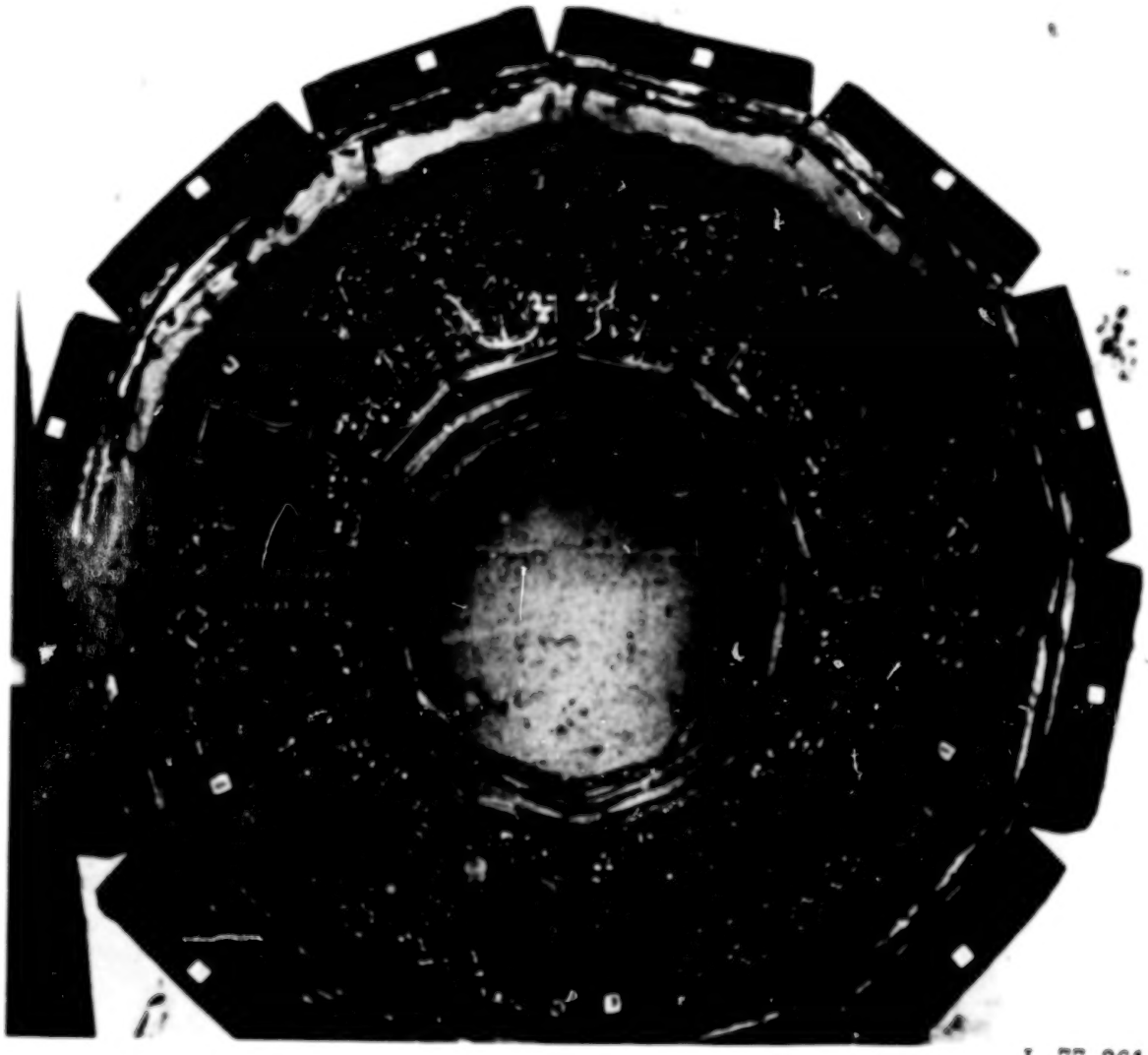
(a) Listening-station assembly.

Figure 3.- Listening station.



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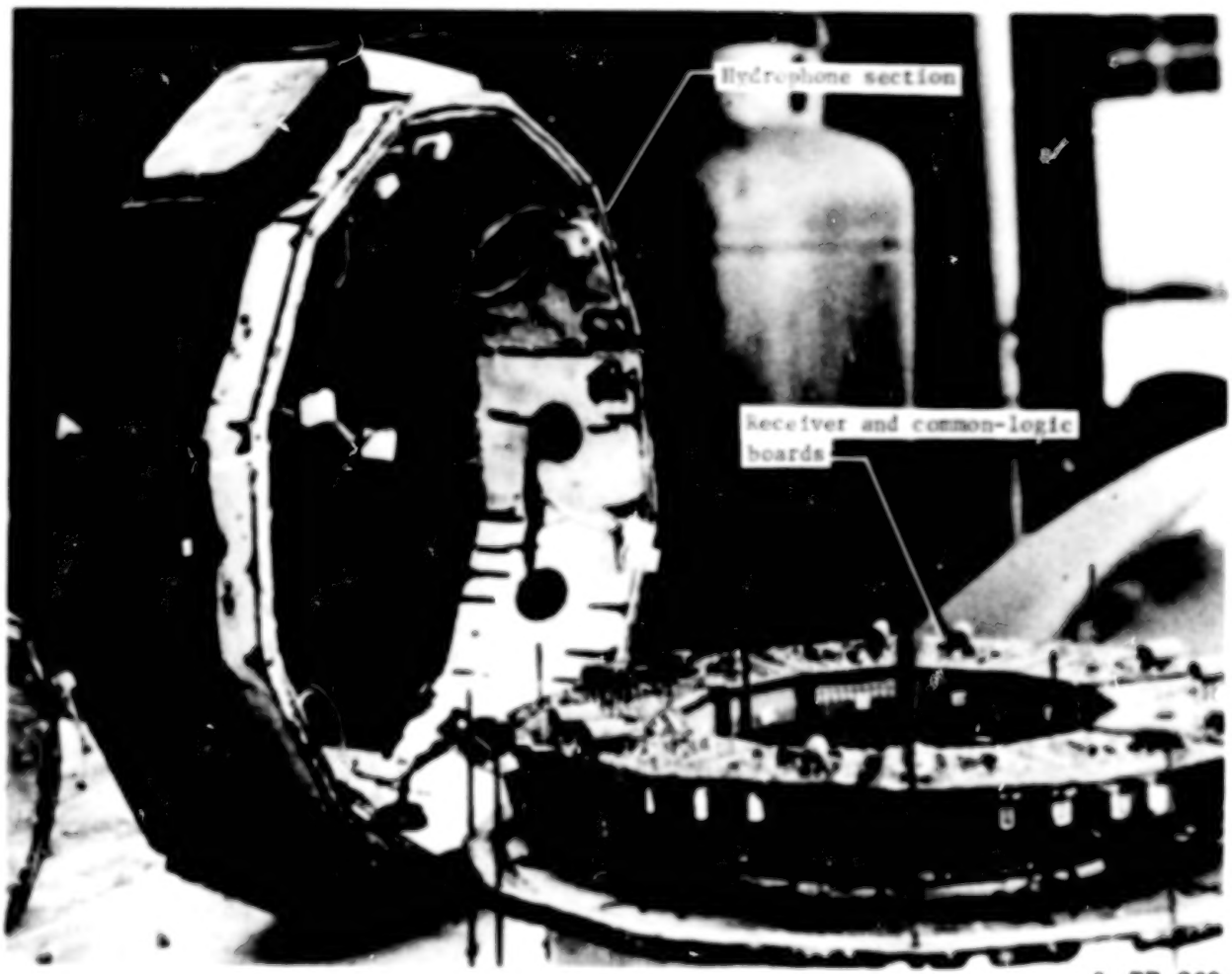
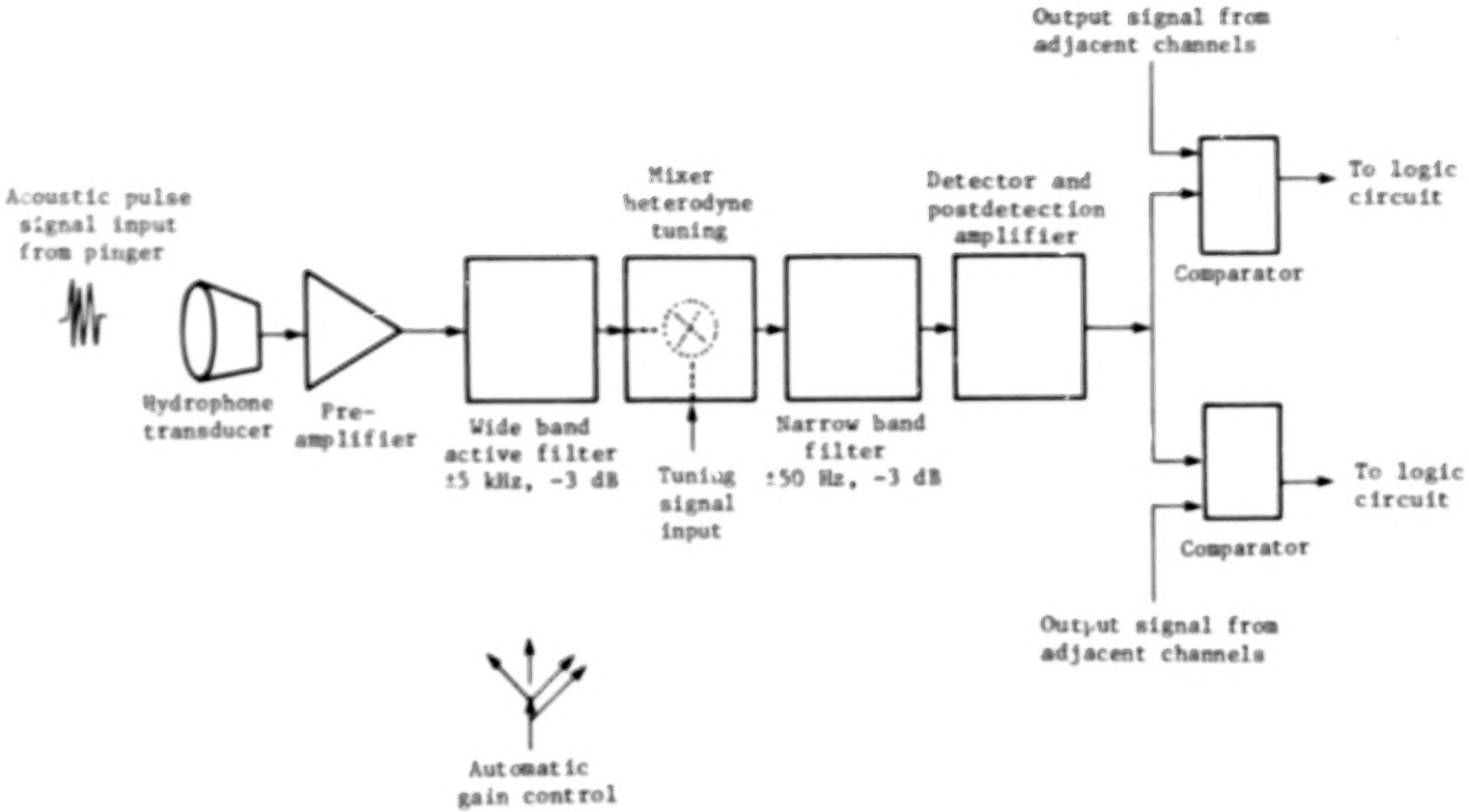
(b) Electronic receivers (top cover removed).

Figure 3.- Continued.



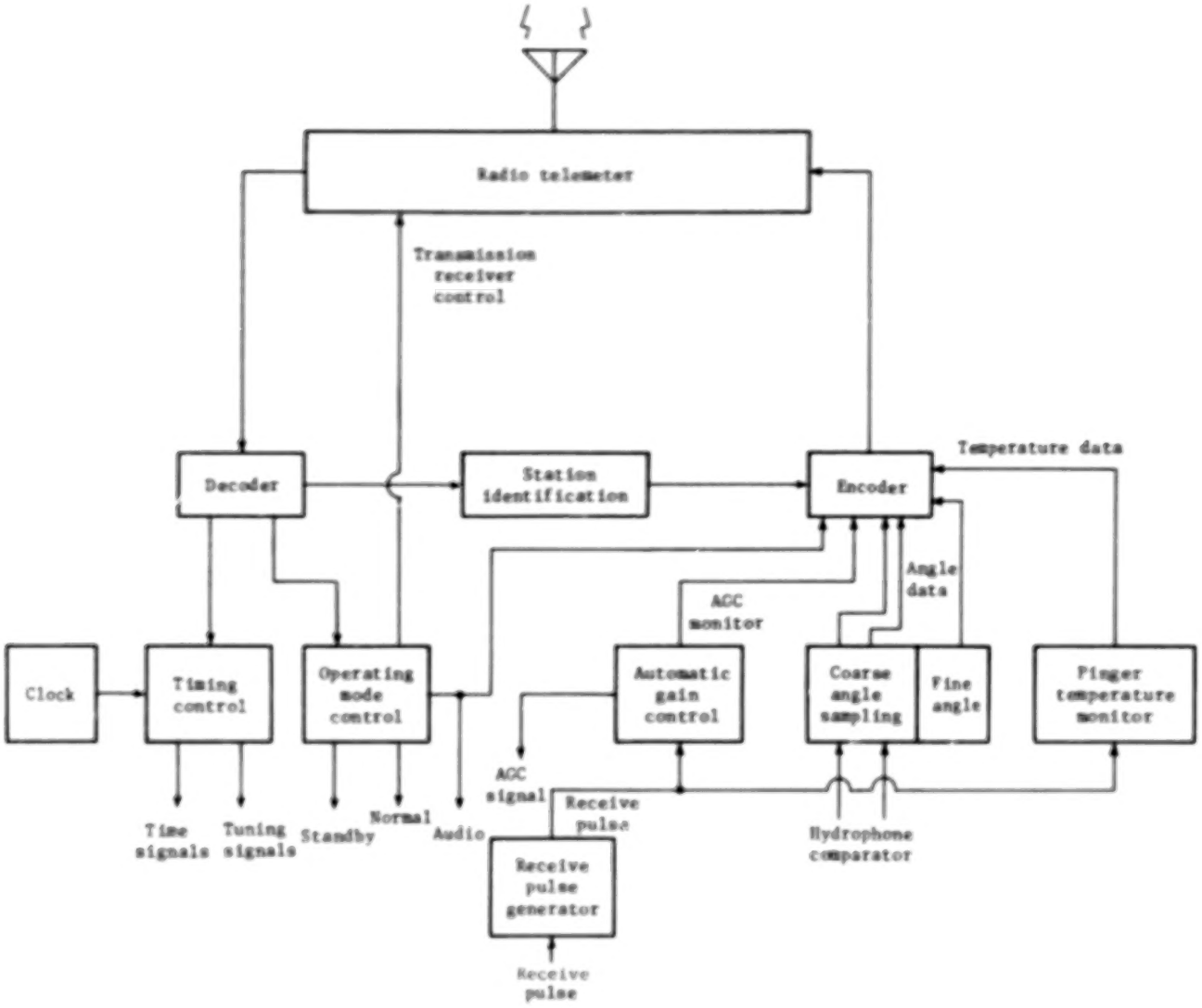
(c) Printed circuit boards.

Figure 3.- Concluded.



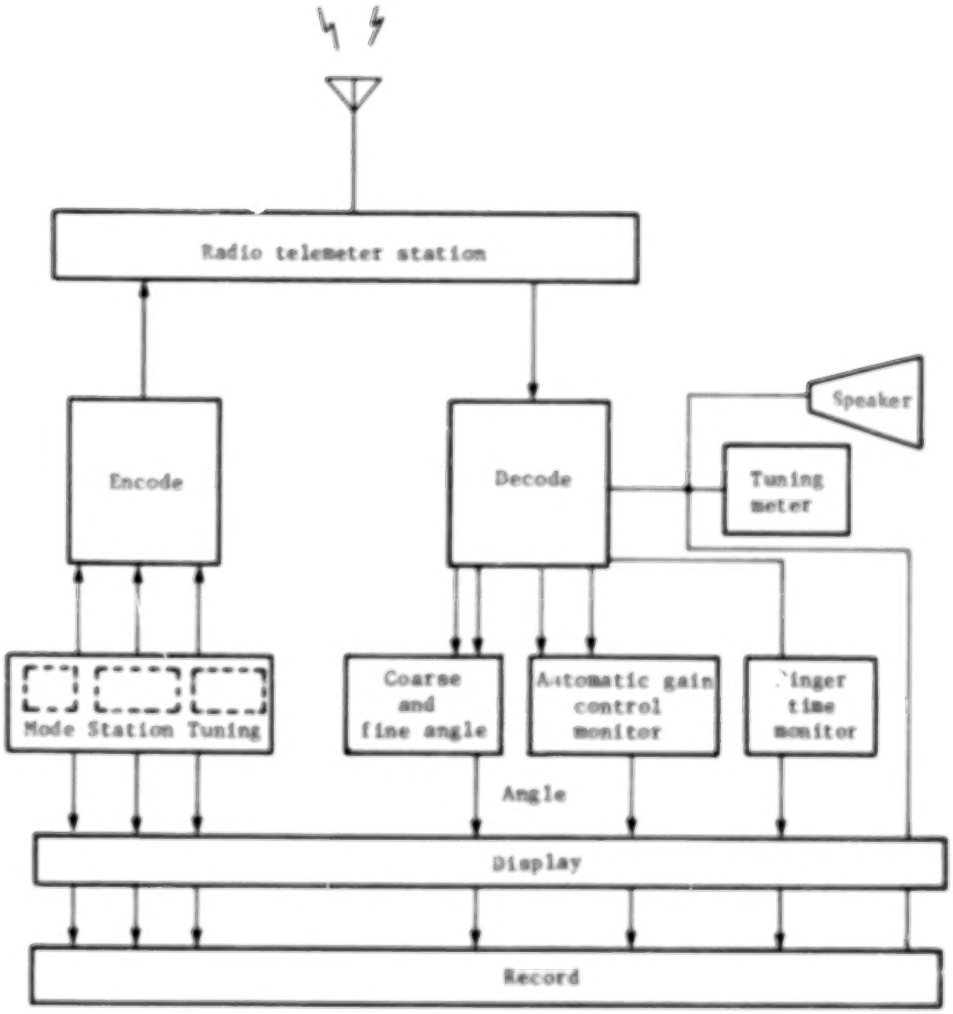
(a) Hydrophone receiver channel.

Figure 4.- Block diagrams of listening station.



(b) Listening-station logic electronics.

Figure 4.- Continued.



(c) Shore data base circuitry.

Figure 4.- Concluded.

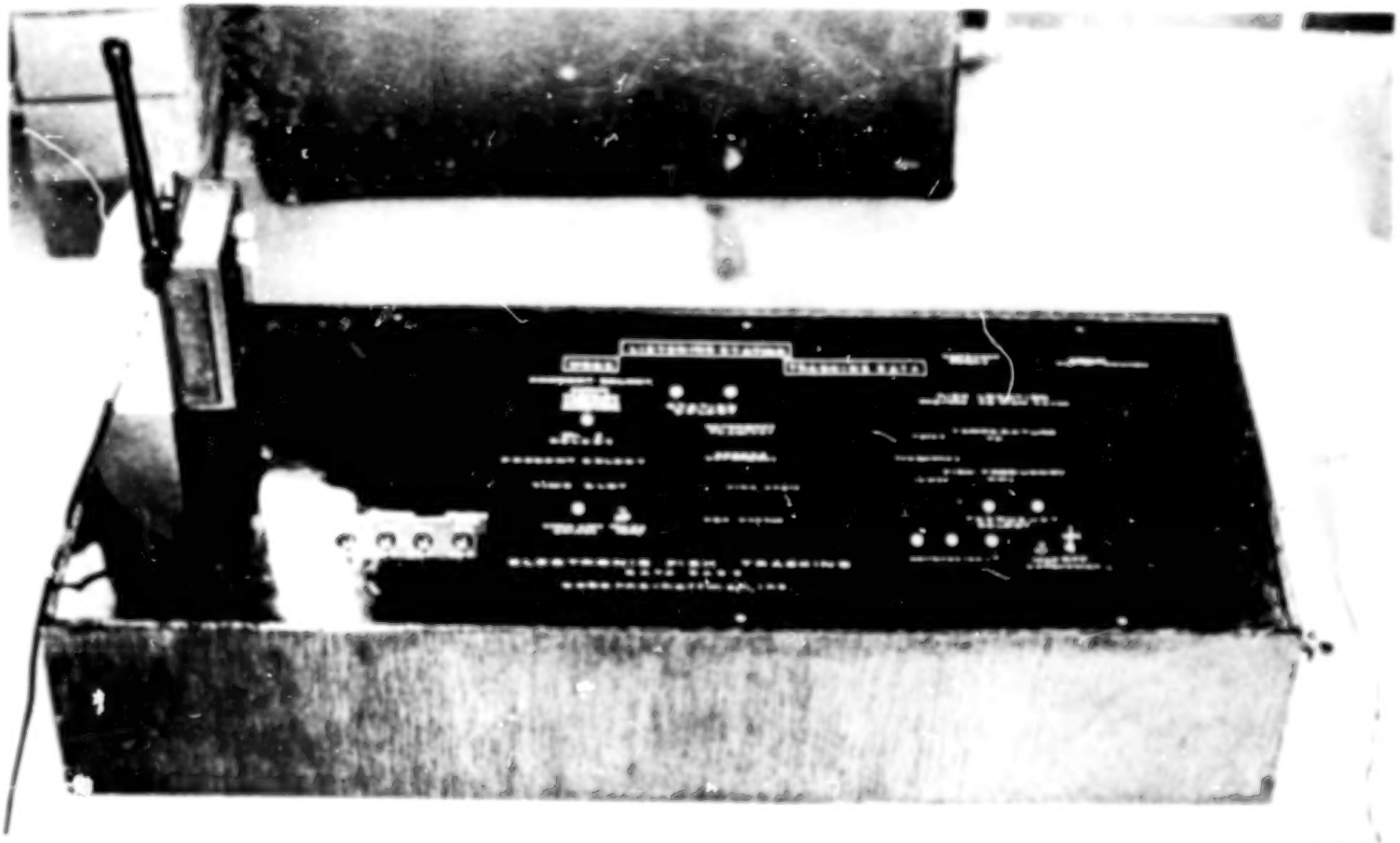


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Figure 5.- Data base.

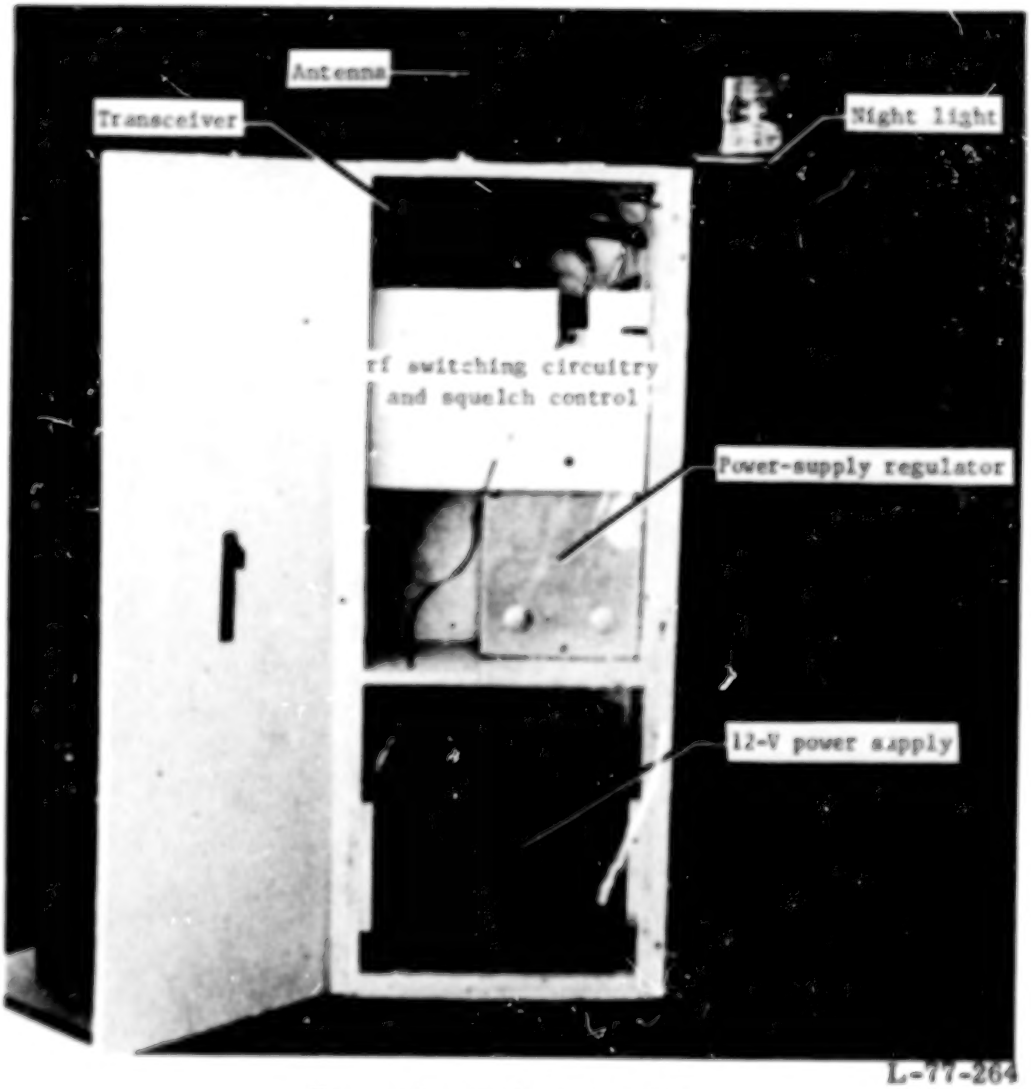
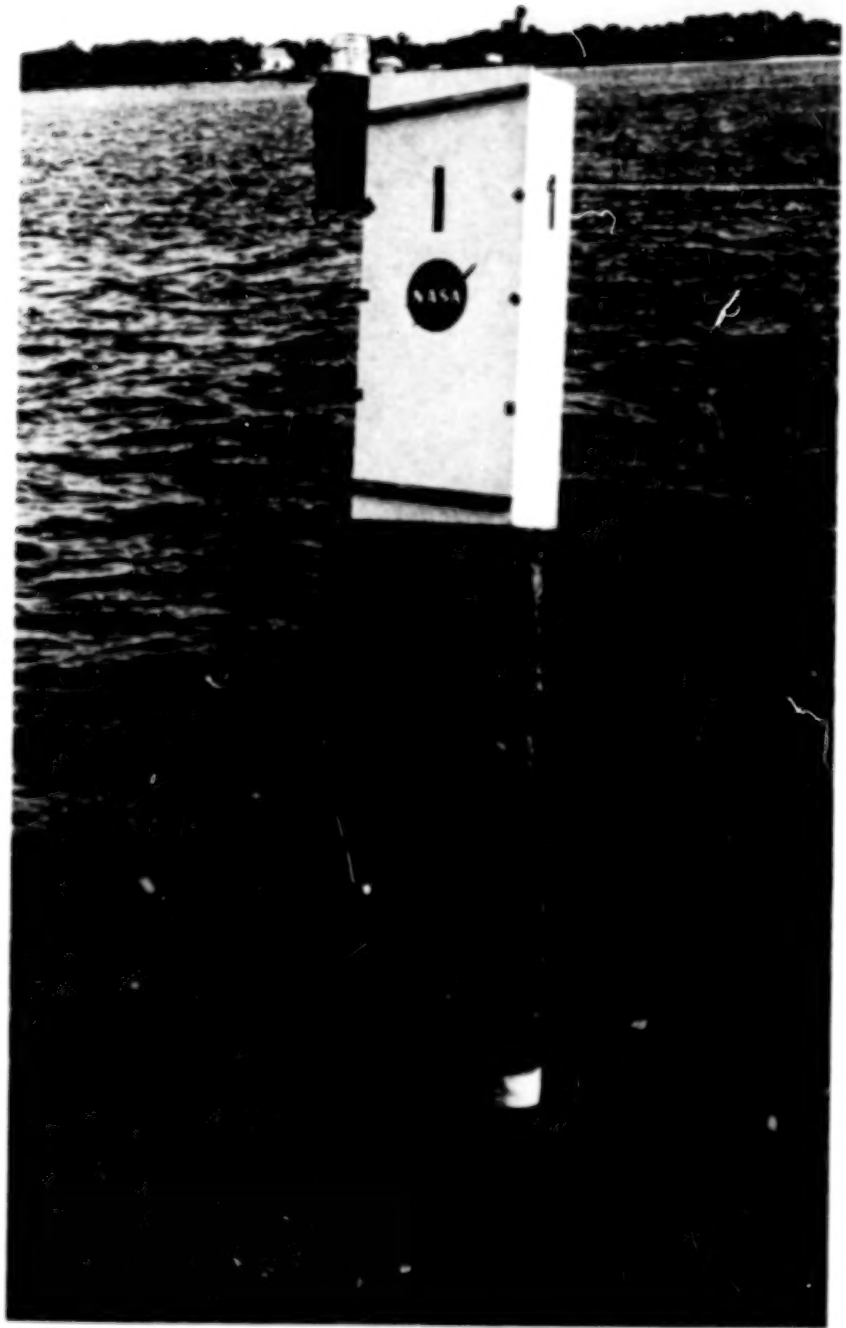


Figure 6.- Radio telemeter.

L-77-265

Figure 7.- Implantation of pinger.



L-77-266

Figure 8.- Field installation of listening station.

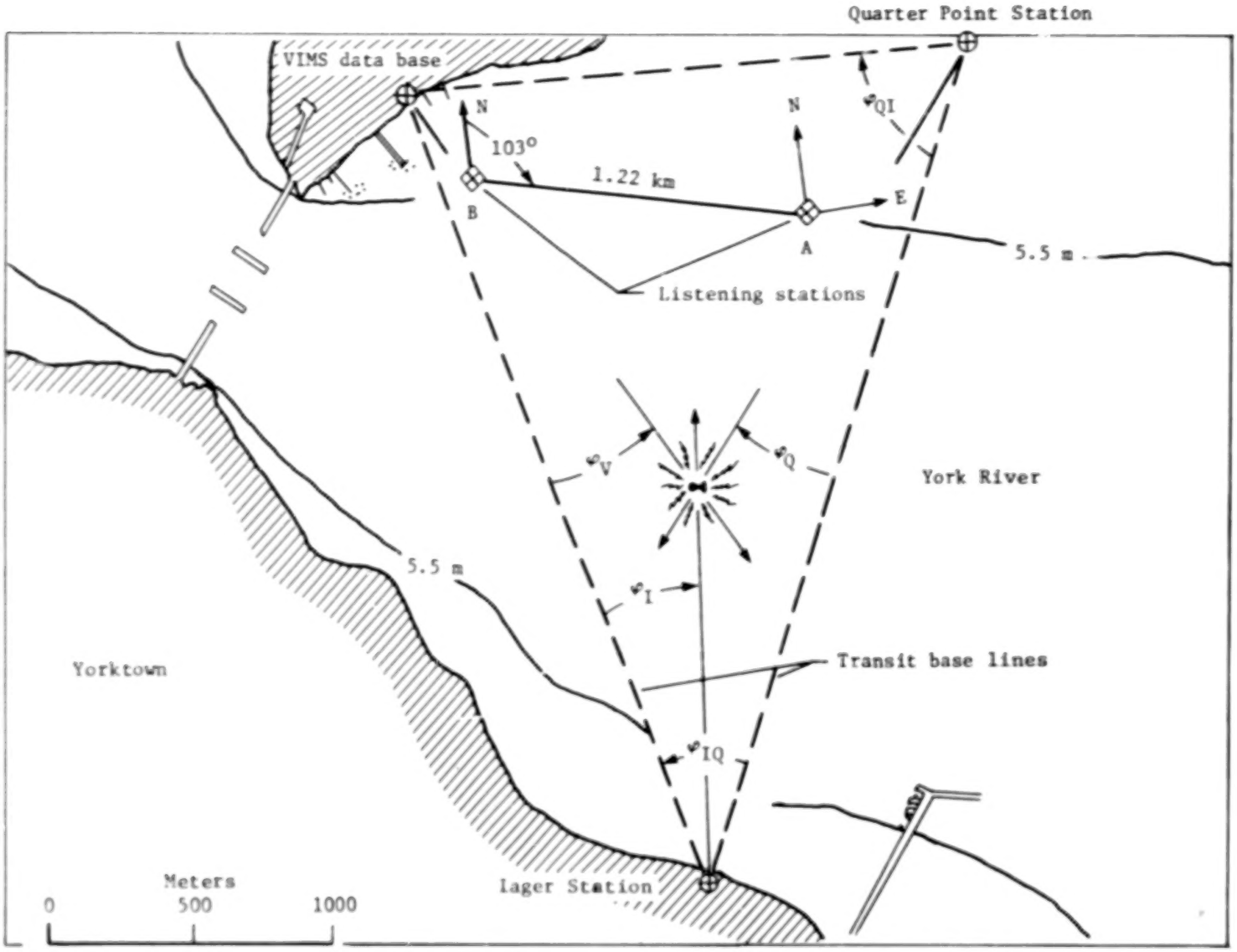


Figure 9.- Locations of fish-tracking system and transit-tracking range.

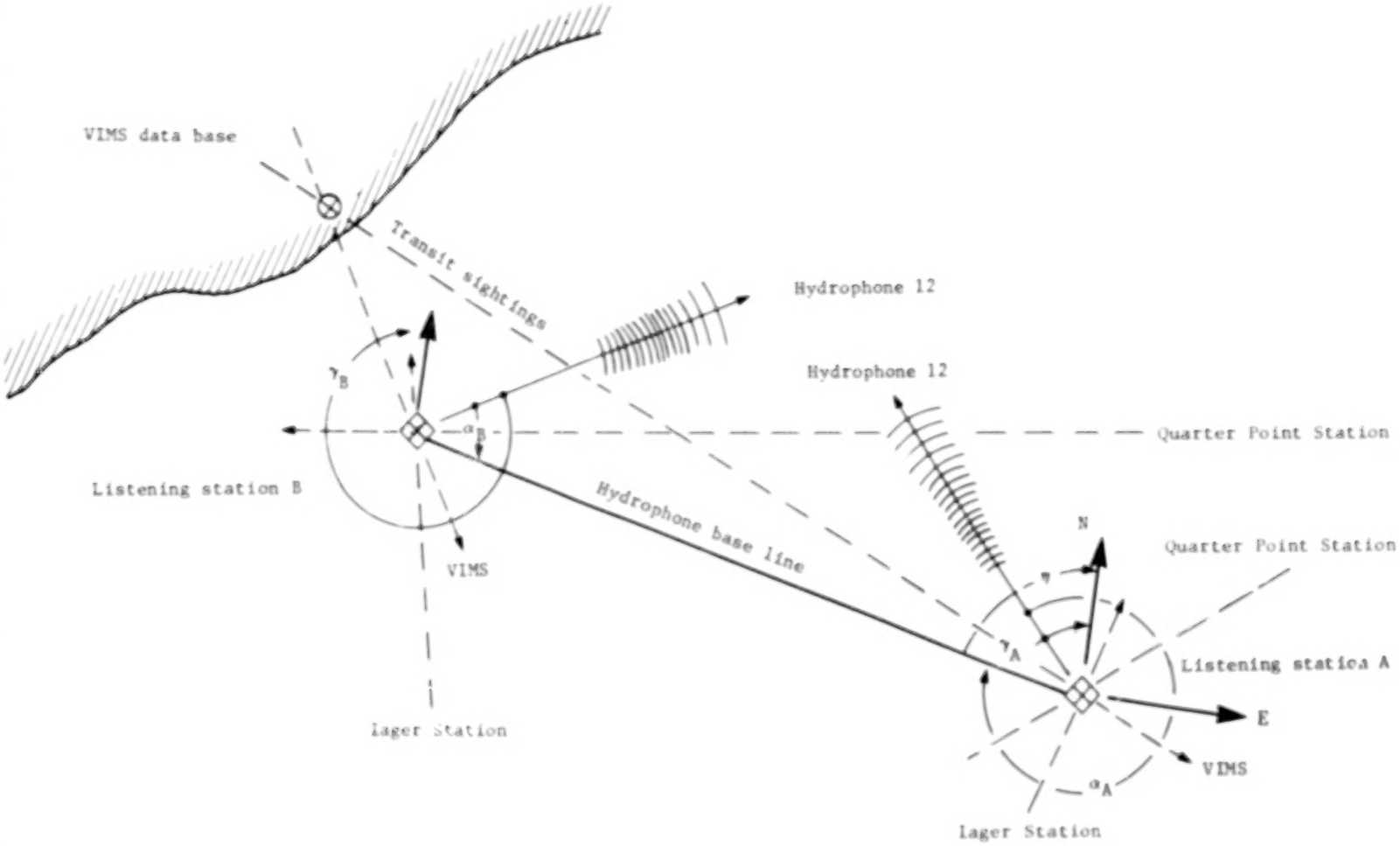
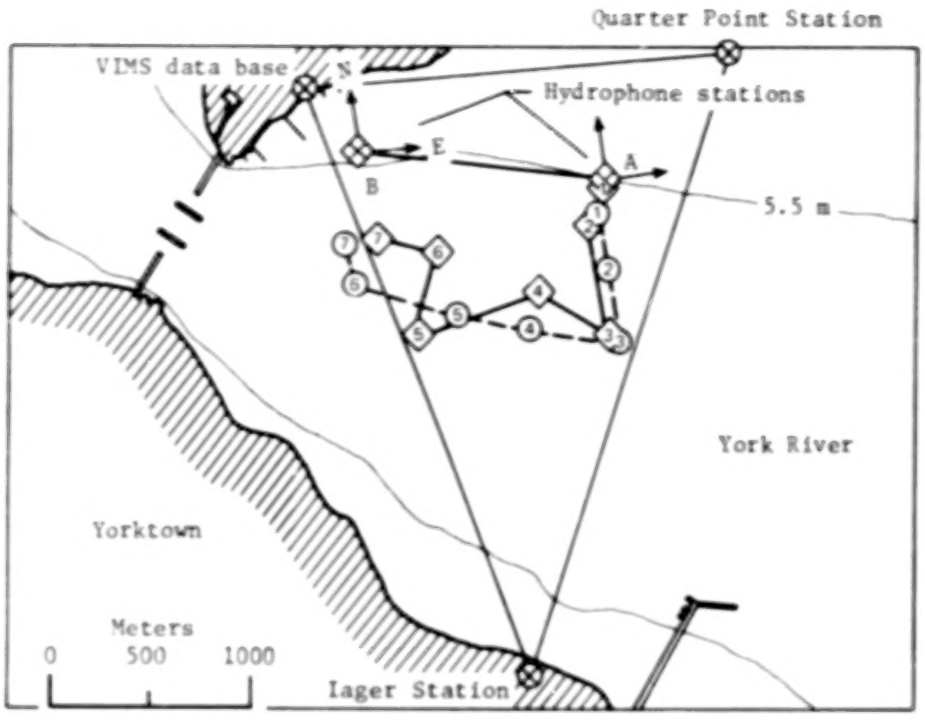
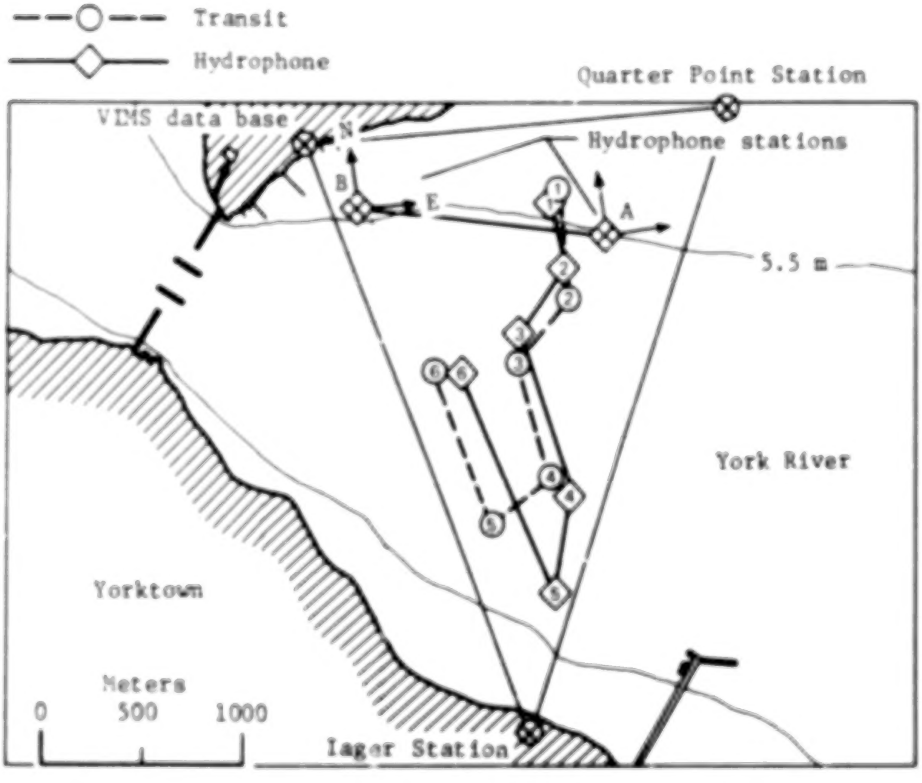


Figure 10.- Parameters for listening-station calibration.

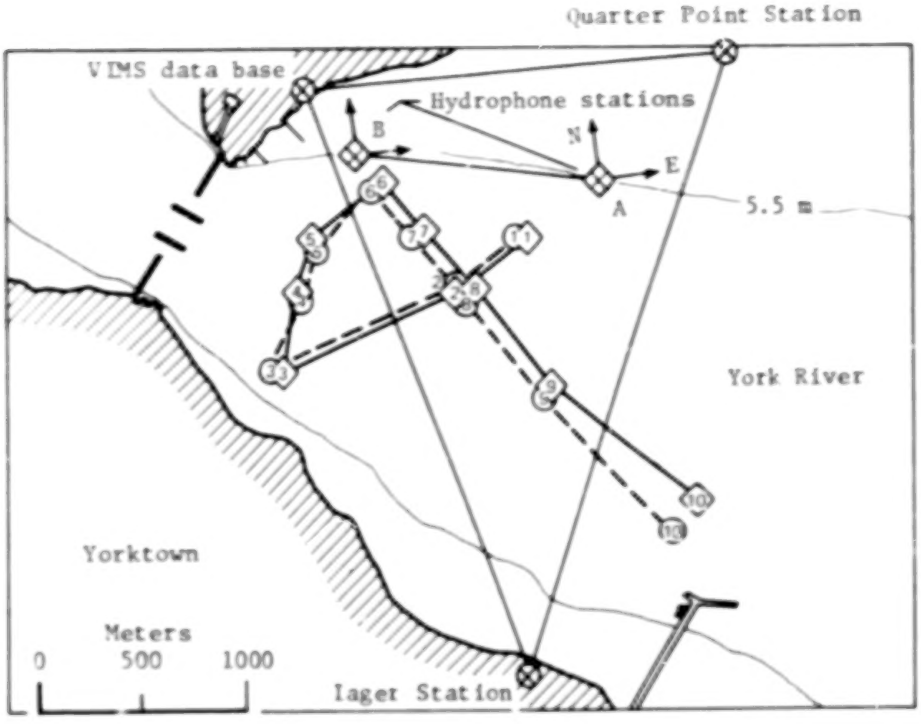


(a) July 23, 1975.

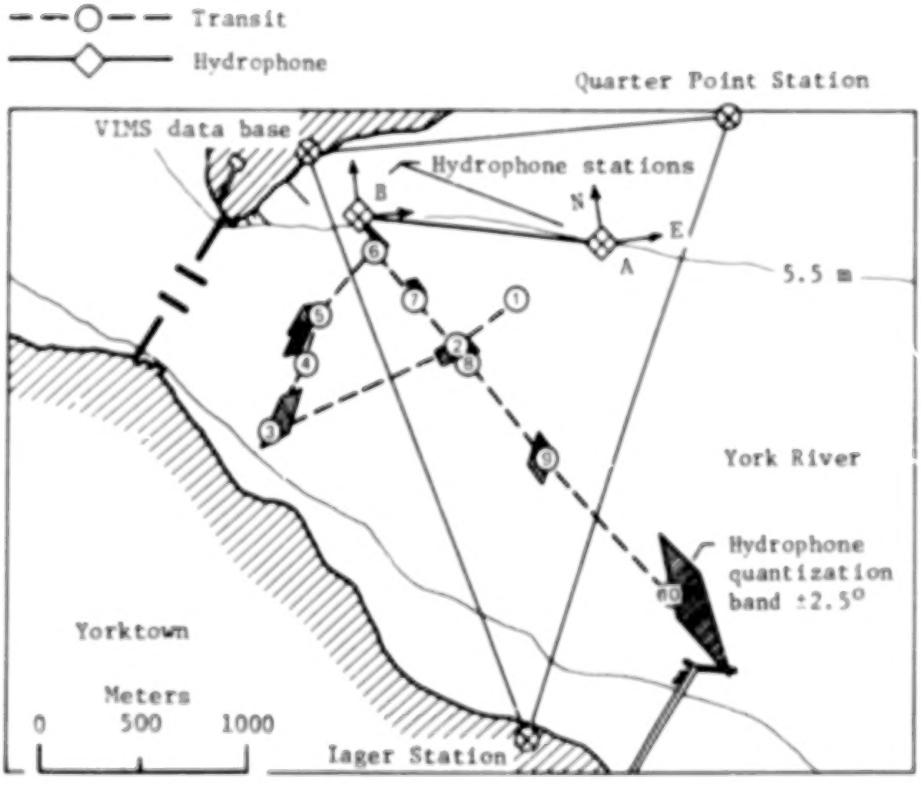


(b) August 13, 1975.

Figure 11.- Comparative results of captive pinger tests.



(c) September 26, 1975.



(d) September 26, 1975 (corrected for calibration bias).

Figure 11.- Concluded.

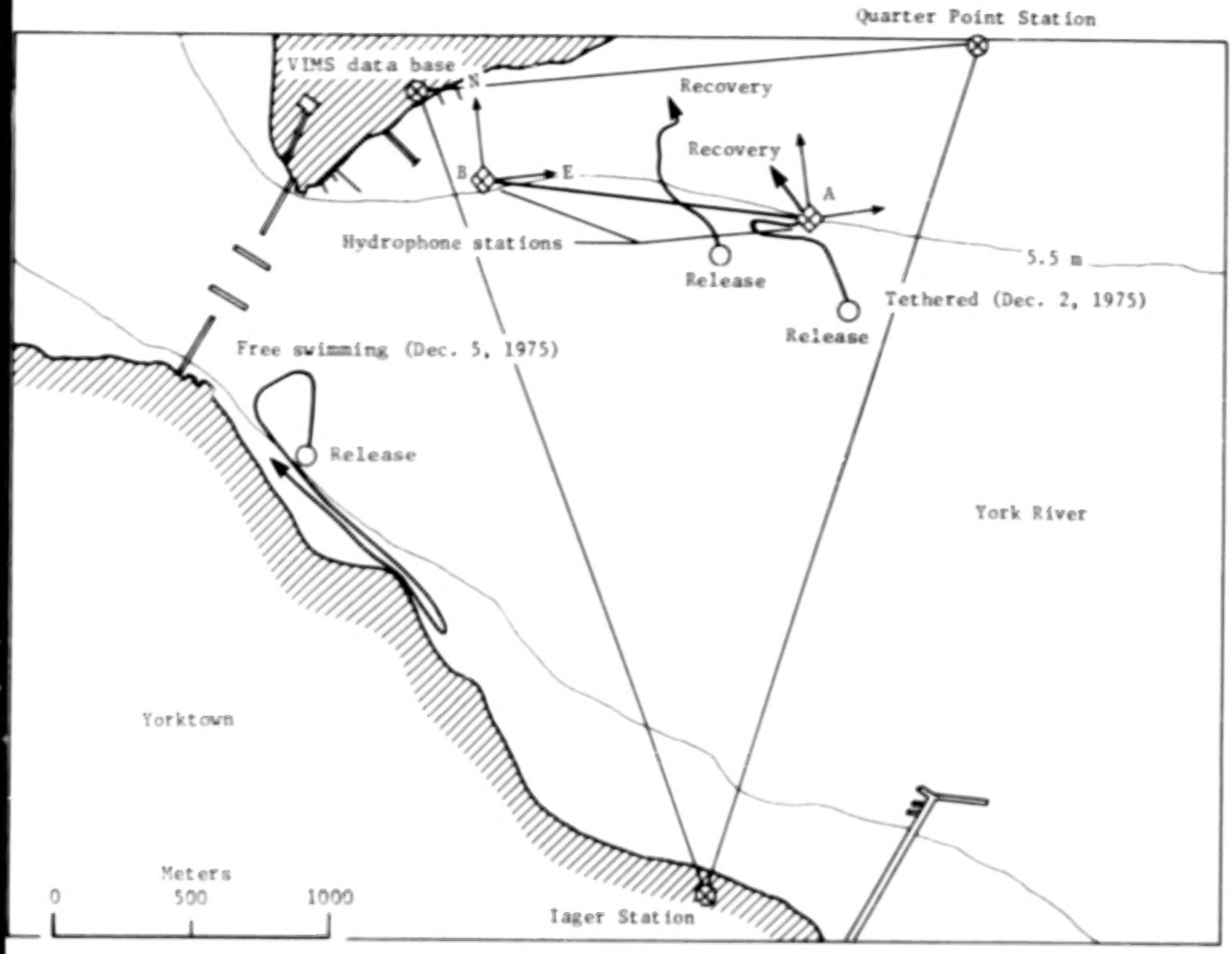
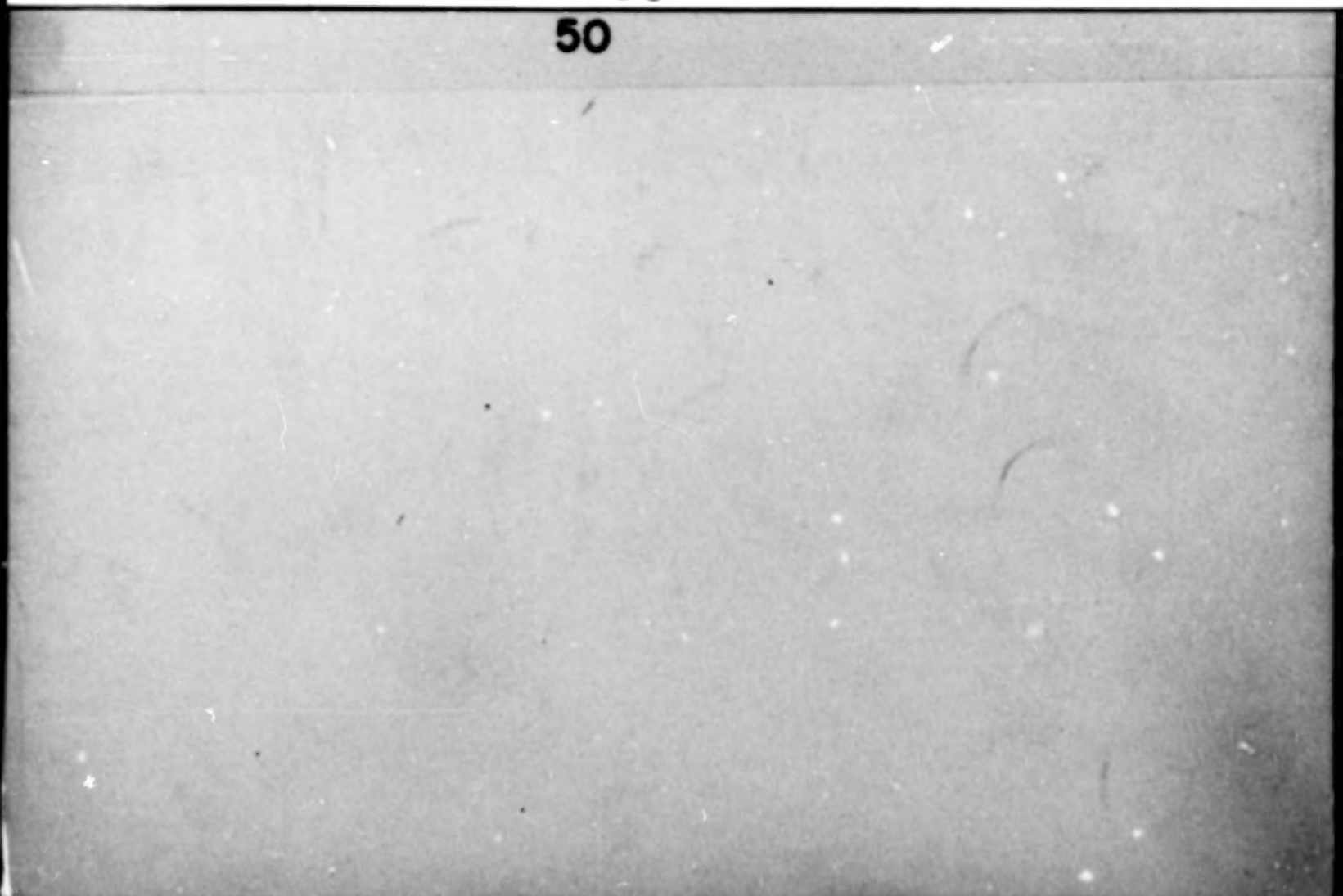


Figure 12.- Tethered and free-swimming fish-tracking results.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